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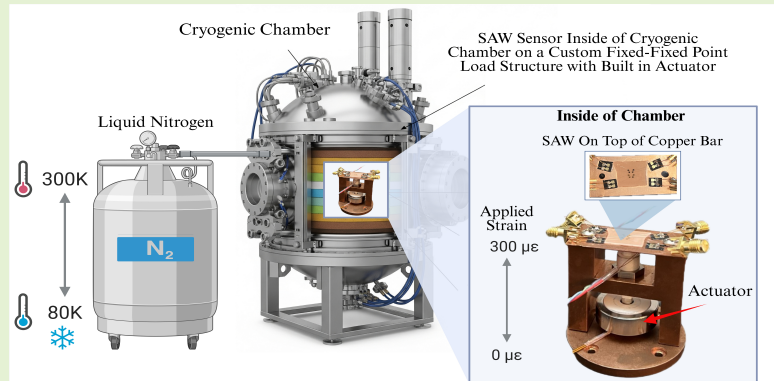
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Temperature and Strain Sensing Characteristics of a 128° YX–Cut LiNbO_3 Rayleigh–Mode SAW Sensor from Room to Cryogenic Temperatures

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Abstract—Accurate, passive, and wireless monitoring of cryogenic hardware is essential for high-energy physics, space propulsion, and biomedical instrumentation. This study quantifies the coupled temperature–strain behavior of Rayleigh-mode surface acoustic-wave (SAW) delay-line sensors fabricated on 128° YX-cut LiNbO_3 . A nonlinear finite element (FE) model incorporating Varshni-based elastic constants, higher-order thermal expansion, and temperature-dependent piezo- and dielectric coefficients was developed and validated experimentally between 280 K and 80 K. Free-standing (first test condition) and bonded/wired (second test condition) devices exhibited indistinguishable thermal responses; the average temperature coefficient of delay (TCD) in the critical cryogenic range from 130 K down to 80 K differed by only 0.15 ppm/K (0.32 %), confirming that bonding-induced stress is negligible. Over 280–80 K the measured TCD was 61.77 ppm/K, while the FE model predicted an equivalent temperature coefficient of frequency (TCF) of -62.74 ppm/K with an overall coefficient of determination $R^2 = 0.998$. In the critical cryogenic interval 130–80 K the TCD fell to 47.66 ppm/K, indicating improved thermal stability at low temperature. Controlled loading (0–300 $\mu\epsilon$) revealed a strain coefficient of delay (SCD) that rises from 0.53 ± 0.02 ppm/ $\mu\epsilon$ at 300 K to 1.05 ± 0.02 ppm/ $\mu\epsilon$ at 80 K. This modest sensitivity confirms that, for temperature sensing, strain is a second-order perturbation above 135 K but must be compensated at deeper cryogenic levels. Overall, this work establishes a predictive multiphysics model together with repeatable wired measurements that confirm the suitability of SAW sensors for temperature and strain monitoring in extreme cryogenic environments, while also providing a baseline for future wireless implementations.

Index Terms—Cryogenic sensing, strain, surface acoustic wave, temperature



I. INTRODUCTION

Operating at cryogenic temperatures is crucial across various industries, including energy, aerospace, and biomedicine. In the energy sector, robust cryogenic systems are needed for high-energy physics accelerators and nuclear fusion reactors [1]. In aerospace, rocket propulsion systems often use cryogenic fuels, such as liquid hydrogen and liquid

oxygen, which must be stored and handled at very low temperatures [2], [3]. The temperature in outer space can drop to extremely low levels, therefore, systems and components must function effectively in these cryogenic conditions. Many instruments used in space exploration, such as infrared telescopes and detectors, require cryogenic temperatures to reduce thermal noise and improve sensitivity [4]. In biomedicine, imaging systems, such as Magnetic Resonance Imaging (MRI) systems and Cryo-electron Microscopy (Cryo-EM), rely on cryogenic operations [5]. Cryosurgery uses extreme cold produced by liquid nitrogen or argon gas to destroy cancer cells and abnormal tissue [6].

Monitoring temperature, strain, and pressure in cryogenic systems is critical to detect abnormalities in the system, such as quenching in superconducting magnets or heat leakage in liquid gas storage [2], [7], [8]. Strain and pressure sensing also play a vital role in ensuring structural integrity during processes like cooling, energizing, and quenching in super-

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conducting magnets, as well as in liquid gas tanks [9], [10]. Currently, electric and optical sensors are common techniques for cryogenic sensing applications. Resistive-type sensors face challenges, including susceptibility to electromagnetic interference (EMI) and heat generation from wires [2], [11]. Optical sensors cannot achieve the function of wireless measurement and face installation challenges with long, fragile optical fibers [9], [12].

SAW technology has attracted much attention for harsh environment applications due to its simplicity, robustness, and passive, wireless operation, eliminating the need for batteries and wires and mitigating challenges associated with wire connections, complex installations, and battery reliability. Fabricated on various piezoelectric substrates, the sensors can operate across a wide temperature range (mK to 1273 K) [13], [14], high radiation environments (up to 400 MRads) [15], and strong electromagnetic interference [16]. These sensors provide unique identification through coding, frequency multiplexing, or time division, enabling simultaneous interrogation of multiple devices [17]. Their cost-effectiveness in large-scale fabrication supports multi-point sensing applications. The surface acoustic waves respond to changes in physical or environmental conditions, such as temperature, pressure, strain, and acceleration, making passive and wireless SAW devices a promising alternative for monitoring cryogenic systems.

Previous studies have investigated the temperature response of SAW sensors using various piezoelectric substrates, including their performance at cryogenic temperatures. Several factors, including substrate material, wave mode, electrode configuration, and packaging, influence the temperature coefficient of frequency (TCF). For instance, GaN/Si-based SAW resonators characterized from 5 K to 423 K (-268 to 150 °C) show that TCF depends on electrode design and packaging, with values of -60 to -70 ppm/K for on-wafer and -40 to -50 ppm/K for packaged devices between 300 and 423 K. As temperature decreases, the magnitude of the TCF decreases, approaching zero near 20 K [18]. Similarly, Nicoloiu et al. reported that AlN/Si and AlN/glass SAW sensors exhibit less negative TCFs as temperature decreases. The AlN/Si device shows -114 ppm/K from 296 to 423 K, -49 ppm/K at 75 K, and nearly zero between 15 and 40 K, with a sign change below 15 K, consistent with GaN/Si behavior. The AlN/glass sensor shows -57 ppm/K at room temperature and -29 ppm/K at 75 K, with further reductions below 75 K [19].

In addition to multilayer thin film-based devices, SAW sensors based on traditional single-crystalline piezoelectric materials have been explored for cryogenic applications due to their stable material properties and simpler fabrication processes. Our group demonstrated that 128° YX LiNbO₃ (LN)-based Rayleigh mode SAW devices exhibit TCFs ranging from -31.1 to -78.9 ppm/K between 78 and 300 K [20]. Zhang et al. recently studied the temperature response of SAW resonators using 128° YX-LN, 64° YX-LN, and 42° YX-LiTaO₃ (LT) substrates from 77 to 293 K. They found that SH-mode devices have lower electromechanical coupling at cryogenic temperatures, while Rayleigh-mode devices show improved coupling. The magnitude of the TCF increases with temperature and

shows a nonlinear frequency-temperature relationship. The 42° YX-LT and 64° YX-LN SH-mode devices exhibit linear behavior from 113–293 K and 153–293 K with TCFs of -31.85 and -52.8 ppm/K, respectively. The 128° YX-LN device shows good linearity in the 153–293 K range with TCFs of -71.65 ppm/K (Rayleigh) and -71.49 ppm/K (SH). At 77 K, the SH-mode TCFs for 42° YX-LT, 64° YX-LN, and 128° YX-LN are -24, -34, and -49.4 ppm/K, respectively, while the Rayleigh-mode TCF for 128° YX-LN is -47.4 ppm/K [21].

These findings highlight that SAW devices based on AlN, GaN, LN, and LT, operating in various modes, can achieve relatively large TCFs, making them promising candidates for temperature sensing in cryogenic environments. In addition to these materials, quartz-based SAW devices have also been characterized at cryogenic temperatures [22]. Quartz offers the advantage of extremely low acoustic loss. However, its very small TCF makes it unsuitable for sensing applications and more appropriate for frequency control. Languisite (LGS), a piezoelectric material well known for its stability at high temperatures, also exhibits good piezoelectric performance at cryogenic temperatures [23]. With its moderate coupling coefficient and TCF, LGS is a good candidate for cryogenic SAW sensing. Among these materials, LN is distinguished by its high electromechanical coupling coefficient, mature fabrication process, wide bandwidth, and large TCF, making it particularly suitable for cryogenic SAW sensing applications. In this study, we focus on SAW devices based on 128° YX LN.

Because SAW propagation is influenced by both temperature and strain, accurate temperature sensing requires minimizing errors caused by strain due to installation, packaging, or external loads. Conversely, reliable strain or pressure measurements require compensation for temperature effects. Therefore, the design and development of SAW sensors for accurate temperature and strain (or pressure) sensing at cryogenic temperatures requires a comprehensive understanding of their dual sensitivity. This necessitates: (1) simulation models capable of accurately predicting SAW responses to temperature and strain variations under cryogenic conditions, and (2) experimental methods to characterize the temperature and strain sensitivities of SAW devices in such environments. To our knowledge, no experimental studies have systematically investigated the strain characteristics of SAW devices across cryogenic temperatures, and no existing simulation models can accurately capture both thermal and strain behaviors in this regime.

This paper provides a novel contribution by theoretically simulating the thermal response and experimentally characterizing the strain responses of 128° YX LN-based SAW devices over a temperature range from room temperature to cryogenic levels, filling a critical gap in the existing literature. The content is organized into five chapters. Chapter II outlines the theory of Rayleigh wave-based SAW sensing and presents an FE model developed to simulate the thermal behavior of bulk LN SAW sensors. Chapter III details the experimental methods used to characterize the thermal and strain responses of the devices. Chapter V discusses both simulation and experimental results, while Chapter VI concludes the study. This work offers a combined theoretical and experimental foundation for the

development of SAW sensors capable of accurate temperature and strain (or pressure) sensing in cryogenic environments.

II. SIMULATION

A. Theory of Rayleigh Wave-based SAW Temperature and Strain Sensor

SAW devices are sensitive to a variety of physical and environmental parameters, including mass loading (m), electrical properties (E), mechanical properties (M_i), and environmental factors (e_v) such as temperature and humidity. As shown by Hoummady *et al.* [24], [25], this relationship can be captured via the chain rule:

$$dV = \left(\frac{\partial V}{\partial m} \right) dm + \left(\frac{\partial V}{\partial E} \right) dE + \left(\frac{\partial V}{\partial M_i} \right) dM_i + \left(\frac{\partial V}{\partial e_v} \right) de_v, \quad (1)$$

where V is the SAW velocity. Small perturbations in each parameter can collectively alter the wave velocity [25]. Consequently, evaluating SAW device behavior under simultaneous variations in temperature and strain is vital for designing robust SAW-based sensors for cryogenic and other specialized applications.

1) Strain Sensitivity: A 128° YX-cut LN substrate, treated as a piezoelectric medium, is subjected to an in-plane strain ε oriented at an angle θ relative to the SAW propagation direction [26]. Let u_i denote the mechanical displacement in the i -th coordinate direction and ϕ the electric potential. The governing equations of motion and electrostatics for a piezoelectric solid with density ρ and initial stress σ_{jk} are given by:

$$\begin{cases} \sigma_{jk} \frac{\partial^2 u_i}{\partial x_j \partial x_k} + c_{ijkl} \frac{\partial^2 u_k}{\partial x_j \partial x_l} + e_{ijk} \frac{\partial^2 \phi}{\partial x_j \partial x_k} - \rho \frac{\partial^2 u_i}{\partial t^2} = 0, \\ e_{jkl} \frac{\partial^2 u_k}{\partial x_j \partial x_l} - \kappa_{jk} \frac{\partial^2 \phi}{\partial x_j \partial x_k} = 0, \end{cases} \quad (2)$$

where $i, j, k, l \in \{1, 2, 3\}$ with Einstein summation implied. Here:

- σ_{jk} is the initial substrate stress,
- c_{ijkl} are the elastic (stiffness) constants,
- e_{ijk} are the piezoelectric constants,
- κ_{jk} are the dielectric constants,
- ρ is the mass density,
- t is time,
- x_1, x_2, x_3 are the coordinate directions ($x_3 = 0$ at the free or metalized surface, see Fig. 1).

According to (2), the applied strain perturbs the propagating SAW and alters its velocity through three independent factors: (1) initial stress, which adds terms to the equation of motion; (2) changes in the elastic constants (c_{ijkl}) of LN; and (3) changes in the density (ρ) of LN [26]. The effective stiffness constants and density become:

$$\begin{aligned} c'_{ijkl} &= c_{ijkl} + c_{ijklmn} \varepsilon_{mn}, \\ \frac{\Delta \rho}{\rho} &= -(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}). \end{aligned} \quad (3)$$

where where $i, j, k, l, m, n \in \{1, 2, 3\}$, c'_{ijkl} is the fourth-rank stiffness tensor under strain, and c_{ijklmn} are the third-order elastic coefficients, and ε_{mn} is the strain tensor [26].

Substituting c'_{ijkl} and $\rho + \Delta \rho$ back into (2) yields an updated wave equation that captures the strain-induced change in wave propagation velocity. With the fundamental relation $v = \lambda f$, where v is the wave velocity, λ is the wavelength (set by the interdigitated transducer (IDT) pitch), and f is the resonant frequency, the relative change of frequency is given by [26]:

$$\frac{df}{f} = \frac{dv}{v} - \frac{d\lambda}{\lambda}. \quad (4)$$

The relative change in the SAW wavelength is typically equivalent to the applied strain in the direction of wave propagation. Based on this relationship and the velocity perturbation derived in (2), the strain coefficient of frequency (SCF) can be expressed as

$$\text{SCF} = \frac{df}{f d\varepsilon} = \frac{dv}{v d\varepsilon} - 1, \quad (5)$$

Similarly, the strain coefficient of delay (SCD) is defined as

$$\text{SCD} = \frac{dt}{t d\varepsilon} \quad (6)$$

where t is the total delay time of the signal. Since the SAW delay time t and the frequency f are inversely related, we have

$$\frac{df}{f} = -\frac{dt}{t}. \quad (7)$$

Consequently, the SCD equals the negative of the SCF:

$$\text{SCD} = -\text{SCF}. \quad (8)$$

In this study, the phase delay shift ($\Delta\phi$), defined as the difference in phase delay between the strained condition (with applied strain ε) and the unstrained condition, was experimentally measured. Given the relation $d\phi/\phi = -dt/t$, the SCD can be then calculated based on the slope of the relative phase shift ($\Delta\phi/\phi$) versus applied strain (ε) plot.

$$\text{SCD} = -\text{slope} \times 10^6, \quad (9)$$

Multiplication by 10^6 converts the result to ppm. The relationship between the relative phase shift and the frequency shift is

$$\frac{d\phi}{\phi} = \frac{df}{f}. \quad (10)$$

In this study, a least-squares linear fit of the relative phase shift versus applied strain plot is used to extract the slope for estimating the SCD.

2) Temperature Sensitivity: Temperature variations alter the wave propagation velocity by affecting the elastic stiffness c_{ijkl} , piezoelectric constants e_{ijk} , dielectric permittivity κ_{jk} , and density ρ . For small deviations ΔT from a reference

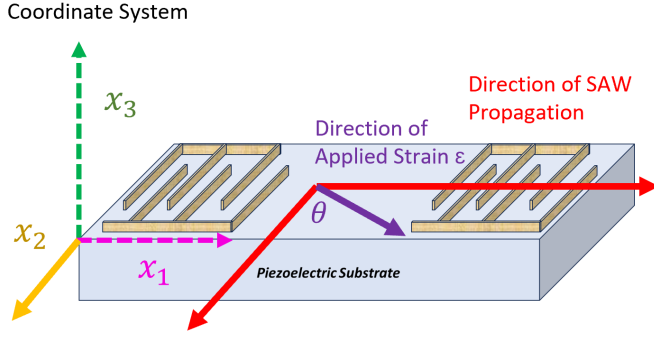


Fig. 1. Coordinate system for modeling applied strain in a rotated LiNbO₃ substrate.

temperature T_0 , these parameters may be linearly approximated [27]:

$$\begin{aligned} c'_{ijkl}(T) &= c_{ijkl} + \left(\frac{\partial c_{ijkl}}{\partial T} \right) \bigg|_{T_0} \Delta T, \\ e'_{ijk}(T) &= e_{ijk} + \left(\frac{\partial e_{ijk}}{\partial T} \right) \bigg|_{T_0} \Delta T, \\ \kappa'_{jk}(T) &= \kappa_{jk} + \left(\frac{\partial \kappa_{jk}}{\partial T} \right) \bigg|_{T_0} \Delta T, \\ \rho'(T) &= \rho [1 - \alpha_\rho \Delta T], \end{aligned} \quad (11)$$

where α_ρ is the volumetric expansion coefficient, and the partial derivatives $\left(\frac{\partial}{\partial T} \right) \big|_{T_0}$ are evaluated at T_0 . Furthermore, temperature-induced thermal stress alters the initial stress (σ_{jk}) in (2). Changes in wavelength arise from dimensional variations due to thermal expansion.

Similar to the SCF, the TCF, defined in (12), depends on the relative changes in wave velocity and wavelength induced by temperature change (ΔT).

$$\text{TCF} = \frac{df}{f dT} = \frac{dv}{v dT} - \frac{d\lambda}{\lambda dT}, \quad (12)$$

Analogous to the SCF–SCD relationship, the temperature coefficient of delay (TCD) can be calculated based on the experimental phase response to thermal variations. The TCD follows the same form as (9), but is obtained from the slope of the relative phase shift ($\Delta\phi/\phi$) versus temperature (T) plot:

$$\text{TCD} = -\frac{d}{dT} \left(\frac{\Delta\phi}{\phi} \right) \times 10^6. \quad (13)$$

Here, the phase delay shift ($\Delta\phi$) is defined as the difference in phase delay between the applied temperature (T_1) and the reference temperature (T_0). While the SCD was extracted from a linear fit of phase versus strain, the TCD was determined by fitting a second-order polynomial to the phase–temperature data, expressed as

$$\frac{\Delta\phi}{\phi}(T) = aT^2 + bT + c, \quad (14)$$

and then taking its first derivative with respect to temperature:

$$\frac{d}{dT} \left(\frac{\Delta\phi}{\phi} \right) = 2aT + b. \quad (15)$$

This derivative was evaluated at the temperatures of interest, and the resulting values were multiplied by -10^6 to yield the TCD in parts per million per Kelvin (ppm/K).

B. Finite Element Modeling (FEM) of Bulk LiNbO₃ SAW Sensor for Temperature

A three-dimensional FE model was developed in COMSOL® Multiphysics to investigate the TCF for a 128° YX-cut LN SAW device with gold IDTs. The analysis was conducted on a periodic unit cell designed for a center frequency of 915 MHz, using a Rayleigh wavelength of $\lambda = 3.948 \mu\text{m}$. The model also incorporated two gold electrodes on a 128° YX-cut LN substrate. For material properties of LN, Tarumi *et al.* reported piezoelectric constants down to cryogenic temperature range [28]. They compared their results at ambient temperature with previously published values and found that e_{31} and e_{33} are significantly overestimated, while e_{15} and e_{22} agree well with earlier studies. Their data also showed that e_{15} and e_{22} exhibit nearly linear behavior down to cryogenic temperatures, suggesting that a first-order temperature dependence provides a reasonable approximation for the piezoelectric parameters down to low temperatures. Given the inaccuracy of e_{31} and e_{33} in [28] and the reliable linear behavior of e_{33} and e_{33} , we therefore adopted piezoelectric constants and first-order temperature coefficients from [29]. The dielectric constants κ_{ij}^S and the density ρ were also treated with first-order dependencies, as higher-order data are unavailable in the literature. The piezoelectric, dielectric, and density constants, along with their first-order temperature coefficients, are summarized in Table I. For a temperature shift $\Delta T = T - T_0$ from the reference $T_0 = 25^\circ\text{C}$,

$$\hat{\rho} = \rho (1 + \text{TC}_\rho \Delta T), \quad (16)$$

$$\hat{e}_{ip} = e_{ip} (1 + \text{TC}_{e_{ip}} \Delta T), \quad (17)$$

$$\hat{\kappa}_{ij}^S = \kappa_{ij}^S (1 + \text{TC}_\kappa \Delta T), \quad (18)$$

where TC_ρ , $\text{TC}_{e_{ip}}$, and TC_κ are the respective temperature coefficients.

TABLE I

SELECTED MATERIAL CONSTANTS AND TEMPERATURE COEFFICIENTS FOR LiNbO₃ AT $T_0 = 25^\circ\text{C}$ [29].

Material Constant	Value	TC ($10^{-4}/^\circ\text{C}$)
<i>Piezoelectric constants (C/m²)</i>		
e_{31}	0.19	2.21
e_{15}	3.7	1.47
e_{33}	1.31	8.87
e_{22}	2.54	0.79
<i>Dielectric constants (10^{-11} F/m)</i>		
κ_{11}	43.6	3.23
κ_{33}	29.16	6.27
<i>Density (10^3 kg/m³)</i>		
ρ	4.7	-0.38

For the elastic constants $C_{ij}(T)$, higher-fidelity data were available (Table II) [28]. In line with Tarumi *et al.* [28], a

temperature-dependent model based on Varshni's equation was adopted:

$$C_{ij}(T) = C_{ij}(0) + \frac{s}{1 - \exp\left(\frac{\Theta_E}{T}\right)}, \quad (19)$$

where $C_{ij}(0)$ is the elastic constant at $T = 0$ K, Θ_E the Einstein temperature for that mode, and s a fitting parameter capturing lattice anharmonicity. This functional form originates from an Einstein-type lattice vibrational model, in which the average oscillator energy is temperature-dependent. Parameter values $\{C_{ij}(0), s, \Theta_E\}$ were determined by Tarumi *et al.* via least-squares fitting to their experimental $C_{ij}(T)$ data. The parameter values and Varshni's equation from Tarumi *et al.* were implemented into the COMSOL® model developed in this study to account for the temperature-dependent nonlinearity of the elastic constants.

TABLE II

COEFFICIENTS OF VARSHNI'S FUNCTION FOR THE ELASTIC CONSTANTS $C_{ij}(T)$ OF LiNbO₃, ADAPTED FROM TARUMI *et al.* [28].

Elastic Constant	$C_{ij}(0)$ (GPa)	s	Θ_E (K)
C_{11}	205.6	10.90	276.2
C_{12}	56.9	4.65	328.8
C_{13}	69.9	3.04	261.0
C_{14}	8.0	0.33	367.0
C_{33}	239.9	8.54	252.8
C_{66}	74.3	3.24	253.3

Thermal expansion was modeled nonlinearly (up to third order), using Bragg-angle data from Kim *et al.* [30]. By measuring shifts in the Bragg angle θ for crystal planes oriented along the principal X , Y , and Z axes, the lattice spacing d was related to temperature T using a polynomial expansion:

$$\frac{d}{d_R} = 1 + \alpha(T - T_R) + \beta(T - T_R)^2 + \gamma(T - T_R)^3, \quad (20)$$

where d_R is the spacing at the reference temperature $T_R = 25^\circ\text{C}$. Table III lists the corresponding expansion coefficients for LN in each principal direction.

TABLE III

EXPANSION COEFFICIENTS FOR LiNbO₃ OVER 0°C – 500°C , REFERENCED TO 25°C . ADAPTED FROM KIM *et al.* [30] AND MIYAZAKI *et al.* [31].

Material	Curie Temp.	Cut	$\alpha \times 10^{-5}$	$\beta \times 10^{-9}$	$\gamma \times 10^{-12}$
LiNbO ₃	1165°C	X	1.44	7.1	-6.34
		Y	1.59	4.9	-6.34
		Z	0.75	-7.7	-5.69

Gold electrodes were assigned an isotropic coefficient of thermal expansion (CTE) of $1.42 \times 10^{-5} \text{ K}^{-1}$. Other gold properties (density, Young's modulus, Poisson's ratio) were taken from the COMSOL® materials library. A free boundary condition was imposed on the top surface, the bottom was clamped, and periodic boundaries were used on the lateral surfaces to emulate an infinite array of cells.

A single temperature sweep was conducted, ranging from 300 K down to 80 K in 20 K increments. At each temperature

point, a prestress eigenfrequency analysis with short-circuited electrodes (zero voltage) was performed to extract the resonant frequency f . The TCF was then computed as (12). The prestress eigenfrequency analysis accounted for thermal stress arising from the CTE mismatch between the gold electrode and LN. However, thermal stress due to bonding between LN and copper was not included in the model, which was assumed negligible given the similar CTEs of LN and copper.

III. EXPERIMENTAL DESIGN

A. Sensor Design & Fabrication

SAW delay-line sensors offer a scalable alternative to resonator-based devices by allowing multiple sensors to be integrated, with each delay line encoding a unique identifier. The device described here operates at a center frequency of 915 MHz and the SAW sensor design parameters are listed in Table IV. Two IDTs and two open reflectors form the core architecture, enabling one- or two-port configurations. In the one-port configuration used in this study, a single IDT functions as both transmitter and receiver, whereas the second IDT and the open reflectors serve only as reflectors. An applied electrical signal excites the inverse piezoelectric effect, generating acoustic waves that propagate across the substrate, reflect, and return to the same IDT.

TABLE IV

SAW SENSOR PARAMETERS.

Parameter	Value
Wavelength (λ)	3.948 μm
IDT Aperture	150 λ
IDT Finger Pairs	11
IDT-IDT Distance	800 λ
IDT-Open Reflector Distance	150 λ
Electrode Material	Au/Cr
Electrode Thickness	90 nm / 10 nm
Substrate Material	128° YX LN

Following the approach described by Kohler *et al.* [32], the sensor was fabricated on a 500 μm thick, 128° YX-cut LN wafer (MTI Corporation, Richmond, California, USA). Chromium (Cr) and Gold (Au) were deposited as IDT materials through electron beam evaporation using a Kurt J. Lesker PVD 75 thin film deposition system (Jefferson Hills, Pennsylvania, USA). PMGI SF6 and ZEP 520A photoresists from MicroChem (Newton, Massachusetts, USA) were utilized during the patterning process, which utilized electron beam lithography on a JEOL JBX-6300FS system (Peabody, Massachusetts, USA).

B. Cryogenic Test Procedure

The SAW devices were characterized using two different test configurations. In the first test condition, the wafer was freestanding on the cooling plate (not bonded to any structures). The IDTs, fabricated onto the LN wafer, were contacted using a spring-loaded microwave probe (0 to 40 GHz, Janis Research Company, LLC, Woburn, MA, USA) connected to a Keysight Technologies network analyzer (model E5061B-005, Santa Rosa, California, USA). Low temperature testing

was carried out in a cryogenic probe station (Janis Research Company, LLC, Woburn, MA) (Fig. 2a), cooled by liquid nitrogen to temperatures as low as 80 K. The sensor was free-standing (unbonded) and placed directly on the cooling plate of the cryogenic chamber. Under the first test condition, only temperature testing was performed. The sensor was cooled from 280 K to 80 K in 10 K increments. At each increment, the S_{11} spectra were recorded.

The recorded signals were acquired with a center frequency of 915 MHz, a frequency span of 250 MHz, and 1601 data points. The signals were then zero-padded, expanding the dataset to 6657 points, corresponding to a frequency range from 0 Hz to 1.04×10^9 Hz. A Fast Fourier Transform (FFT) was applied to convert the signals into the time domain, where a time gate was applied with $t_{\min} = 0.30 \mu\text{s}$ and $t_{\max} = 0.34 \mu\text{s}$. This step was used to identify the index of the main acoustic pulse peak, isolate the relevant reflection, and reduce the influence of multi-reflections. The time-gated signals were then transformed back into the frequency domain via FFT, and phase shift values at 915 MHz were extracted at each temperature set point [32]. In addition, we computed the peak magnitude (in dB) of the gated $|S_{11}(f)|$ within the original measurement band as a time-gated reflection metric.

For the second test condition, the SAW sensor was bonded to a 0.5 mm thick copper bar (McMaster-Carr, Elmhurst, Illinois, USA) using a cyanoacrylate-based adhesive (Model CN, Texas Measurements, College Station, TX, USA) to enable low-temperature strain testing. A custom fixed-fixed point-load apparatus was developed to impose controlled strain on the SAW sensors (Fig. 2b). Electrical connections were established via wedge wire bonding using a Kulicke and Soffa model 4526 system (Singapore) with 30-gauge copper wires soldered to SMA connectors (Fig. 3). The network analyzer was connected to the sensor through the SMA connectors. The device incorporates a CLA-2601 actuator (JPE, Azielaan, Maastricht-airport, Netherlands), which incrementally increases strain from 0 to $300 \mu\epsilon$ in $50 \mu\epsilon$ steps. A commercial strain gauge (CFLA-3-350, Tokyo Measuring Instruments Lab) was bonded to the underside of a copper substrate to monitor and calibrate the applied strain, and a DP32PT gauge meter (OMEGA Engineering, Norwalk, CT, USA) was used for strain measurement. The actuator applied a normal displacement to bend the copper bar, resulting in tensile strain on the top surface and compressive strain on the bottom surface along the longitudinal axis. The SAW delay line (top) and the reference strain gauge (bottom) were both aligned with this axis to measure axial strain.

For the second test condition (bonded and wired sensor), two sets of experiments were conducted. First, to evaluate the effects of bonding and wiring on sensor signals and sensitivities, temperature testing was performed following the same procedure and signal processing as used for the first test condition tests. The second set of experiments involved characterizing the SCD in a wide temperature range (80 K to 300 K). The first sequence measured the SCD at temperatures of 300 K, 267 K, 234 K, 201 K, 168 K, and 135 K. The second sequence targeted a lower-temperature range (135 K, 120 K, 105 K, 90 K, and 80 K). Each temperature level was subjected

to two complete loading-unloading cycles to confirm repeatability of the measurements. Two distinct test sequences were performed under identical loading conditions ($0 \mu\epsilon - 300 \mu\epsilon$). Signal processing was consistent with the first experiment, except that the analyzed time window was defined between $t_{\min} = 1.60 \mu\text{s}$ and $t_{\max} = 1.67 \mu\text{s}$.

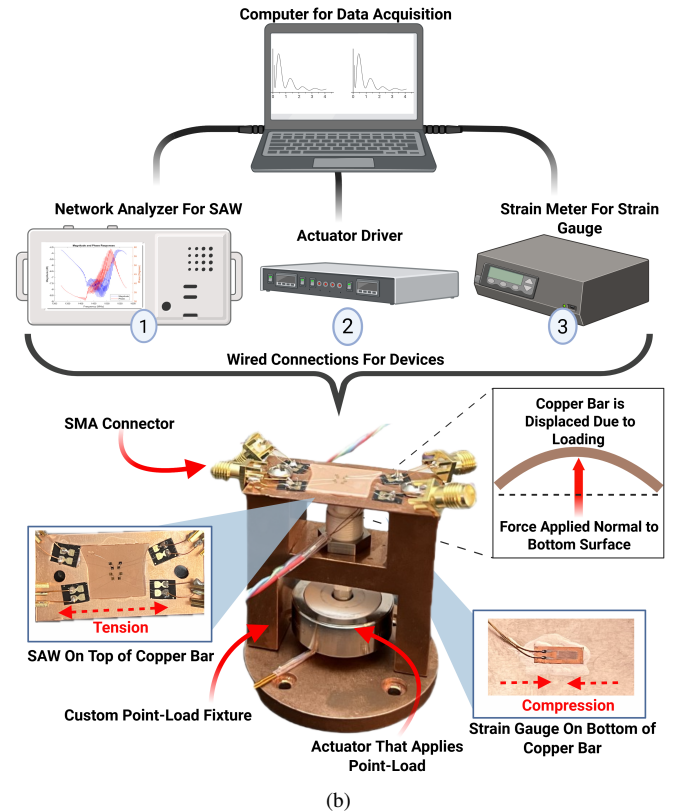
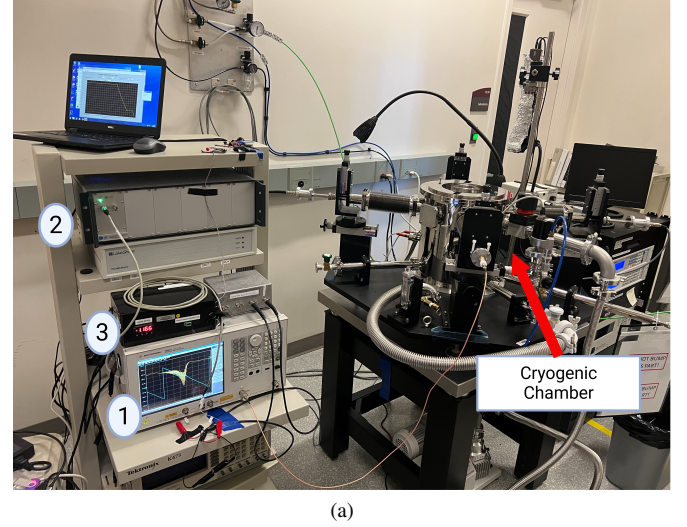


Fig. 2. Experimental setup for low-temperature evaluation of the SAW sensor inside a cryogenic chamber. (a) Setup of the cryogenic chamber cooled by liquid nitrogen. Labeled components: (1) network analyzer, (2) actuator driver, and (3) strain gauge meter. (b) Block diagram and close-up view of the SAW sensor mounted on a custom fixture. Diagrams created using BioRender.

IV. RESULTS AND DISCUSSION

A. Thermal Response

Fig. 4a, 4b, and 4c present the experimental time-domain S_{11} response at 280 K comparing the first and second test conditions, the computed peak magnitude (in dB) of the gated $|S_{11}(f)|$ within the original measurement band as a time-gated reflection metric, and the relative phase shift at zero strain across temperatures from 280 K to 80 K using both first and second test conditions, respectively. The reference temperature used here is 280 K. We found that contact resistance, stray inductance, and dielectric dispersion introduced by wire connections add only a minor amount of damping to signal strength.

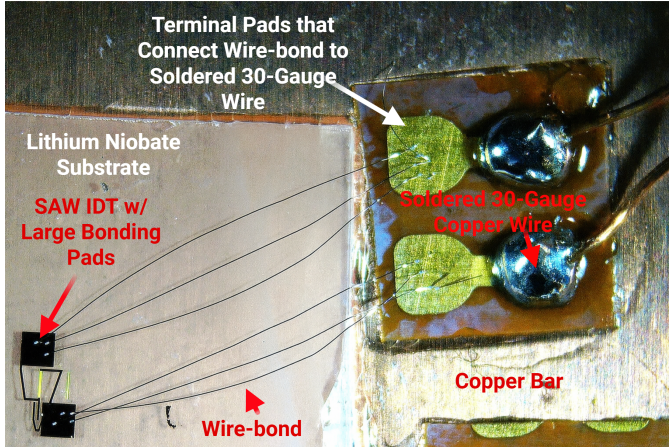


Fig. 3. Up-close view of the bonded sensor configuration illustrating the wire-bond connections and 30-gauge leads soldered to the SMA connector. Multiple wires were bonded for redundancy to ensure continued operation in the event that a wire bond breaks during thermal cycling.

While the present results are based on a one-port configuration, it is also important to consider the expected differences in a two-port configuration. If the present measurements were conducted in a two-port configuration, the device response would be characterized by both reflection (S_{11}) and transmission (S_{21}) rather than reflection alone. Serhane *et al.* performed a finite-element comparison of one-port and two-port SAW resonators and a delay line on an Al/AlN/Si stack at ~ 440 MHz, showing that the one- and two-port resonators exhibit nearly identical temperature sensitivities (22.74 vs. 23.17 ppm/°C) and comparable quality factors (2858 vs. 2903) [33]. The primary distinction was in the measurement response: the two-port configuration yielded a resonance peak in S_{21} , whereas the one-port exhibited a resonance notch in S_{11} . Their results further indicated that with increasing temperature, the S_{21} magnitude remained essentially constant, while the S_{11} magnitude decreased slightly, with both responses shifting toward lower frequency. Consistent with these trends, a two-port realization of the present study would be expected to provide transmission-based data with reduced reflection artifacts and improved measurement stability, while maintaining comparable sensitivity. In the current setup, measurements are limited to S_{11} due to cryogenic chamber constraints, thus, two-port testing will be explored in future work.

The time-gated reflection amplitude, defined as the peak of the gated $|S_{11}(f)|$ within the measured band, monotonically

strengthens with decreasing temperature, changing from -34.73 dB at 280 K to -29.65 dB at 80 K (net $+5.08$ dB), indicating reduced effective loss along the gated path (Fig. 4b). Across the full temperature sweep, the phase-shift traces from the two test conditions are practically indistinguishable (Fig. 4c), yielding an inter-method coefficient of determination of $R^2 = 0.999$. In the critical cryogenic range from 130 K down to 80 K, the average TCD is 47.34 ppm/K for the first test condition and 47.49 ppm/K for the second test condition (Fig. 4c). The absolute difference of 0.15 ppm/K corresponds to a relative deviation of just 0.32 %, which is well within an acceptable range. These results indicate that thermal stress induced by bonding between the LiNbO₃ (LN) substrate and the supporting copper substrate has a negligible effect on device TCD. The temperature change does not introduce sufficient initial stress in (2) to cause a significant change in wave-propagation velocity; therefore, the assumption of negligible thermal stress from bonding in our finite-element model is justified.

Fig. 4d compares the simulated relative frequency shift ($\Delta f/f$) with the average experimental relative phase shift ($\Delta \phi/\phi$) for temperatures from 280 K to 80 K for four trials ($N = 4$). The reference temperature used in Fig. 4d is 280 K. The simulated thermal response agrees well with the average experimental results, giving an overall $R^2 = 0.998$ for the 280–80 K range and validating the consistency between the measurements and the finite-element modeling assumptions. Both simulated and experimental data exhibit a negative slope, indicating negative TCF and positive TCD values. The slope becomes less negative as temperature decreases, meaning the TCF becomes less negative and the TCD less positive.

The simulated average TCF is -62.74 ppm/K (TCD = 62.74 ppm/K) over the 280–80 K range. Restricting the interval to 130–80 K yields a TCF of -46.24 ppm/K (TCD = 46.24 ppm/K). At 280 K the simulated TCD is 83.36 ppm/K, while at 80 K it decreases to 42.11 ppm/K. Experimentally, the average TCD is 61.77 ppm/K from 280–80 K, and 47.66 ppm/K in the 130–80 K interval. At 280 K the experimental TCD is 80.57 ± 2.14 ppm/K, and at 80 K it is 42.96 ± 0.26 ppm/K. Table V summarizes the comparison between simulated and experimental TCD values, where the experimental results are reported as mean $\pm$ std with $N = 4$.

The negative TCF (or positive TCD) arises from an increase in propagation velocity and a decrease in wavelength with decreasing temperature. Velocity increases because the elastic constants rise, although the density and piezoelectric coefficients of LiNbO₃ fall, whereas wavelength decreases due to the positive coefficient of thermal expansion along the propagation direction. Tarumi *et al.* showed that all elastic constants C_{ij} increase monotonically with decreasing temperature, while their temperature dependence (i.e., $|dC_{ij}/dT|$) diminishes at low T . This flattening of $C_{ij}(T)$ contributes to the improved thermal stability of 128° YX LiNbO₃ SAW devices below 135 K. The close agreement between the simulated and experimental results over 280–80 K ($R^2 = 0.998$) confirms that elastic constants dominate the thermal response, while first-order approximations for piezoelectric and dielectric parameters are sufficient to reproduce the observed behavior.

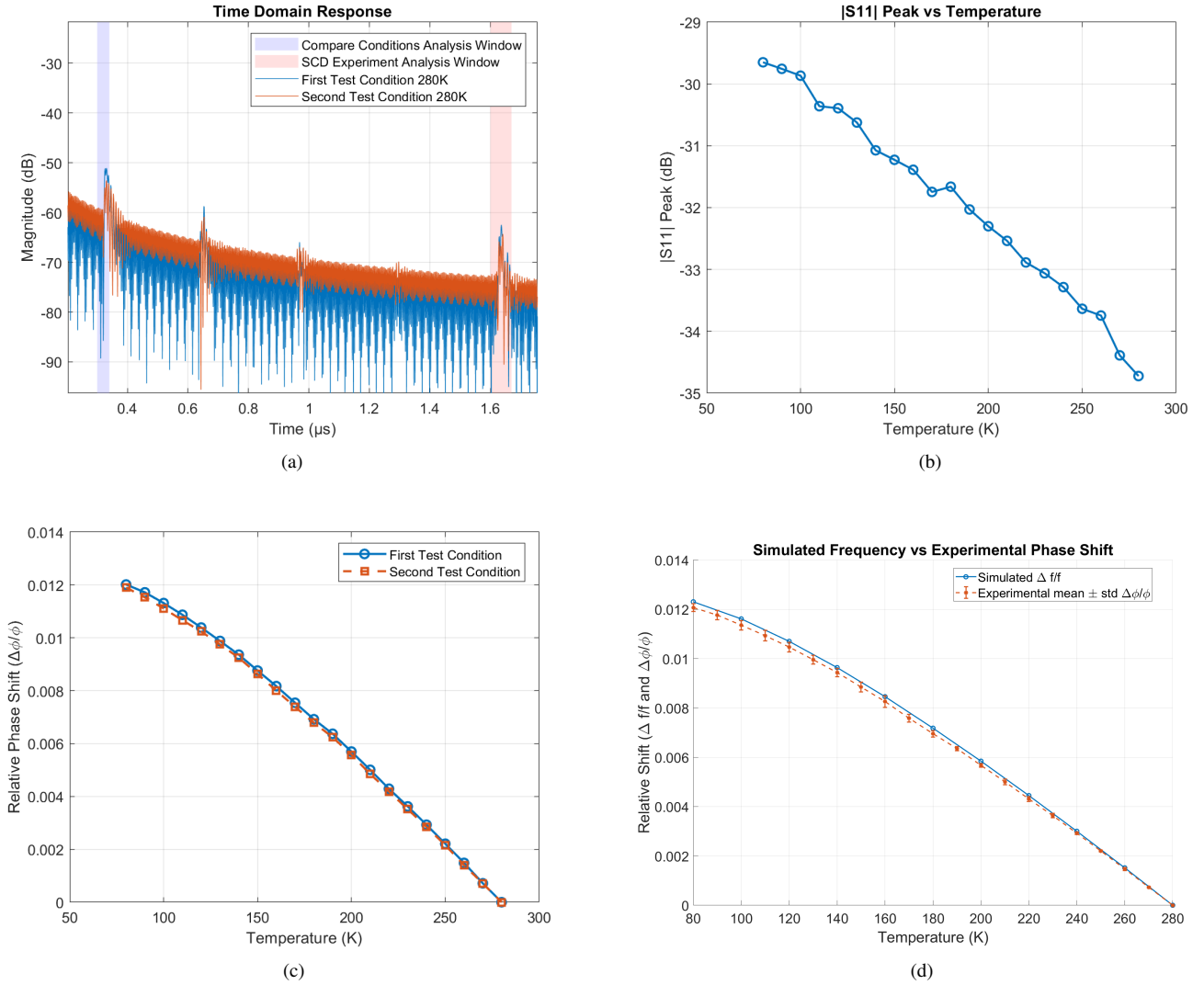


Fig. 4. (a) Time-domain S_{11} response of the LN SAW device after inverse Fourier transform and zero-padding, comparing the first (blue trace) and second (orange trace) test conditions. (b) The computed peak magnitude (in dB) of the gated $|S_{11}(f)|$ within the original measurement band as a time-gated reflection metric from 280 K down to 80 K. (c) Relative phase shift versus temperature (280 K to 80 K) under cryogenic cooling, comparing the first (solid curve) and second (dashed curve) test conditions. (d) Relative simulated and average experimental temperature analysis from 280 K down to 80 K.

Our simulation results agree with previous studies of bulk 128°YX -LN Rayleigh-wave SAW devices, which typically report TCF values between -70 and -80 ppm/K [27], [34]. However, earlier models estimated TCF only at room temperature and did not capture the nonlinear thermal response over wider temperature ranges. To the best of our knowledge, this is the first report of a FE model that accurately predicts the nonlinear thermal behavior of a SAW device from room temperature down to cryogenic levels.

The strong agreement between simulation and experiment confirms that our model accurately captures both the intrinsic thermal response of the LN substrate and practical electrode and mounting effects across the tested temperatures. The small TCD discrepancy may stem from higher-order effects not included in the remaining first-order parameters; nevertheless, the close correspondence shows that the chosen nonlinear parameters effectively capture the substrate's low-temperature

response.

In the present work, the refined Rayleigh-mode devices exhibit an experimental TCD at 80 K of 42.96 ± 0.26 ppm/K, while the simulation predicts 42.11 ppm/K. The strong agreement between the experimental and simulated TCD values at 80 K reinforces the reliability of the updated electrode geometry and wafer quality. Zhang *et al.* recently examined SAW resonators on 128°YX -LN substrates between 77 K and 293 K, finding that Rayleigh-mode devices exhibit improved coupling as temperature decreases, consistent with our observation of enhanced signal strength at cryogenic temperatures. Their devices show good linearity in the 153–293 K range with TCFs of -71.65 ppm/K; at 77 K, the TCF is -47.4 ppm/K [21]. Our present experimental TCD of 42.96 ± 0.26 ppm/K at 80 K is slightly smaller in magnitude, but the trend of decreasing TCD as temperature falls is consistent; residual differences likely stem from dissimilar electrode con-

TABLE V

 COMPARISON OF SIMULATED TCD VALUES AND EXPERIMENTAL TCD VALUES (REPORTED AS MEAN $\pm$ STD, $N = 4$).

Temperature (K)	Simulated TCD (ppm/K)	Experimental TCD (ppm/K)
280	83.36	80.57 $\pm$ 2.14
270	—	78.69 $\pm$ 2.03
260	79.24	76.81 $\pm$ 1.92
250	—	74.93 $\pm$ 1.81
240	75.11	73.05 $\pm$ 1.70
230	—	71.17 $\pm$ 1.59
220	70.99	69.29 $\pm$ 1.47
210	—	67.41 $\pm$ 1.36
200	66.86	65.53 $\pm$ 1.25
190	—	63.65 $\pm$ 1.14
180	62.74	61.77 $\pm$ 1.04
170	—	59.89 $\pm$ 0.93
160	58.61	58.01 $\pm$ 0.82
150	—	56.12 $\pm$ 0.71
140	54.49	54.24 $\pm$ 0.61
130	—	52.36 $\pm$ 0.51
120	50.36	50.48 $\pm$ 0.41
110	—	48.60 $\pm$ 0.33
100	46.24	46.72 $\pm$ 0.26
90	—	44.84 $\pm$ 0.24
80	42.11	42.96 $\pm$ 0.26

figurations, signal-processing techniques, and intrinsic wafer quality. Although differing in substrate configuration and wave mode, Lee *et al.* studied cryogenic wideband shear-horizontal SAW devices on a Y-cut LiNbO₃/SiO₂/sapphire platform, reporting TCFs of approximately -17.8 ppm/K below 100 K and -61.03 ppm/K from 125 K to 300 K [35]. These findings underscore that LiNbO₃-based composite structures can exhibit different thermal sensitivities at low temperatures, consistent with the reduced TCF/TCD magnitudes observed in our study.

B. Strain Response

Fig. 5a shows the relative phase shift versus applied tensile strain (0–300 $\mu\epsilon$) at multiple thermal set points from 300 K down to 80 K. Each color-coded series corresponds to a distinct temperature under both loading and unloading conditions. Table VI summarizes the average SCD for each temperature between 300 K and 80 K. Values range from about 1.05 ± 0.02 ppm/ $\mu\epsilon$ at the lowest temperature to approximately 0.53 ± 0.02 ppm/ $\mu\epsilon$ at 300 K. Compared to the TCD of the device, which is 80.57 ± 2.14 ppm/K at 280 K and 42.96 ± 0.26 ppm/K at 80 K, the SCD is significantly smaller. At room temperature, a strain of 300 $\mu\epsilon$ induces a phase shift of roughly 159 ppm, equivalent to the shift caused by a 1.98 ± 0.05 K temperature change; at 80 K, the same strain results in a phase shift of about 315 ppm, corresponding to a 7.33 ± 0.05 K temperature change. Therefore, when the device is used for strain sensing (Fig. 5a), temperature effects become significant, limiting such applications to temperature-stable environments unless the device is modified, for example, by adopting a multilayer structure based on LN thin films to reduce the TCD. Conversely, when used for temperature sensing (Fig. 5b), the influence of strain is negligible at room temperature; however, at cryogenic temperatures, the strain effect must be considered. Fig. 6a and 6b illustrate the relative phase shift of the SAW sensor as a function of cryogenic temperature from 135 K down to 80 K, measured at strain

levels ranging from 0 to 300 $\mu\epsilon$. A consistent increase in relative phase shift was observed with decreasing temperature across all strain levels, and a consistent decrease in relative phase shift was observed with increasing strain.

TABLE VI

 COMBINED (LOADING + UNLOADING) SCD STATISTICS FOR TWO TRIALS AT EACH TEMPERATURE BETWEEN 300 K AND 80 K. VALUES ARE MEAN $\pm$ STD; $N = 4$ PER TEMPERATURE.

Temperature (K)	SCD (ppm/ $\mu\epsilon$)
300	0.53 $\pm$ 0.02
267	0.68 $\pm$ 0.04
234	0.80 $\pm$ 0.06
201	0.79 $\pm$ 0.02
168	1.01 $\pm$ 0.04
135	0.93 $\pm$ 0.06
120	0.85 $\pm$ 0.17
105	0.99 $\pm$ 0.04
90	1.07 $\pm$ 0.02
80	1.05 $\pm$ 0.02

The positive SCD arises from a reduction in wave-propagation velocity and an increase in propagation path length under applied strain. For a 128° YX LiNbO₃-based device, simulations suggest that the velocity decrease stems mainly from reductions in elastic constants, attributed to negative third-order elastic constants, even though accompanying increases in initial stress and decreases in material density with applied strain tend to raise the velocity [26]. The observed increase in TCD at lower temperatures may be related to the temperature dependence of third-order elastic constants. Another possible contributor is temperature-induced variation in strain-transfer efficiency from the substrate to the device, as bonding-material properties evolve during cooling or heating.

Li *et al.* reported a rising LN SAW strain sensitivity from about 98 Hz/ $\mu\epsilon$ at 303 K to 108 Hz/ $\mu\epsilon$ at 523 K [36]. To the best of our knowledge, however, no prior study, other than the present work, directly compares SCD values for SAW sensors at cryogenic temperatures. This work thus addresses a critical gap by extending strain-based SAW analysis into low-temperature regimes, where property datasets are less established. Future efforts will develop an FE model that incorporates comprehensive thermomechanical coupling, including $\partial^2 V / (\partial \epsilon \partial T)$, to reconcile theoretical predictions with experimental trends.

In comparison with the analytical model value of 0.995 ppm/ $\mu\epsilon$ and the experimentally reported 0.712 ppm/ $\mu\epsilon$ by Xu *et al.* [26], the experimentally measured value of 0.53 ± 0.02 ppm/ $\mu\epsilon$ in this study is lower. One likely cause is the quality and uniformity of the adhesive layer, which, as also noted by Xu *et al.*, significantly affects the strain transfer efficiency from the mounting structure to the SAW substrate [26]. Inconsistent bonding or variations in adhesive thickness may generate localized stress gradients that reduce coupling efficiency. Similar issues have been reported elsewhere: Liu *et al.* showed that increasing adhesive thickness weakened strain transfer in a one-port SAW resonator [37], and Sreejith *et al.* found that their SAW sensor achieved only one-third of its theoretical sensitivity due to adhesive effects [38]. Refining the

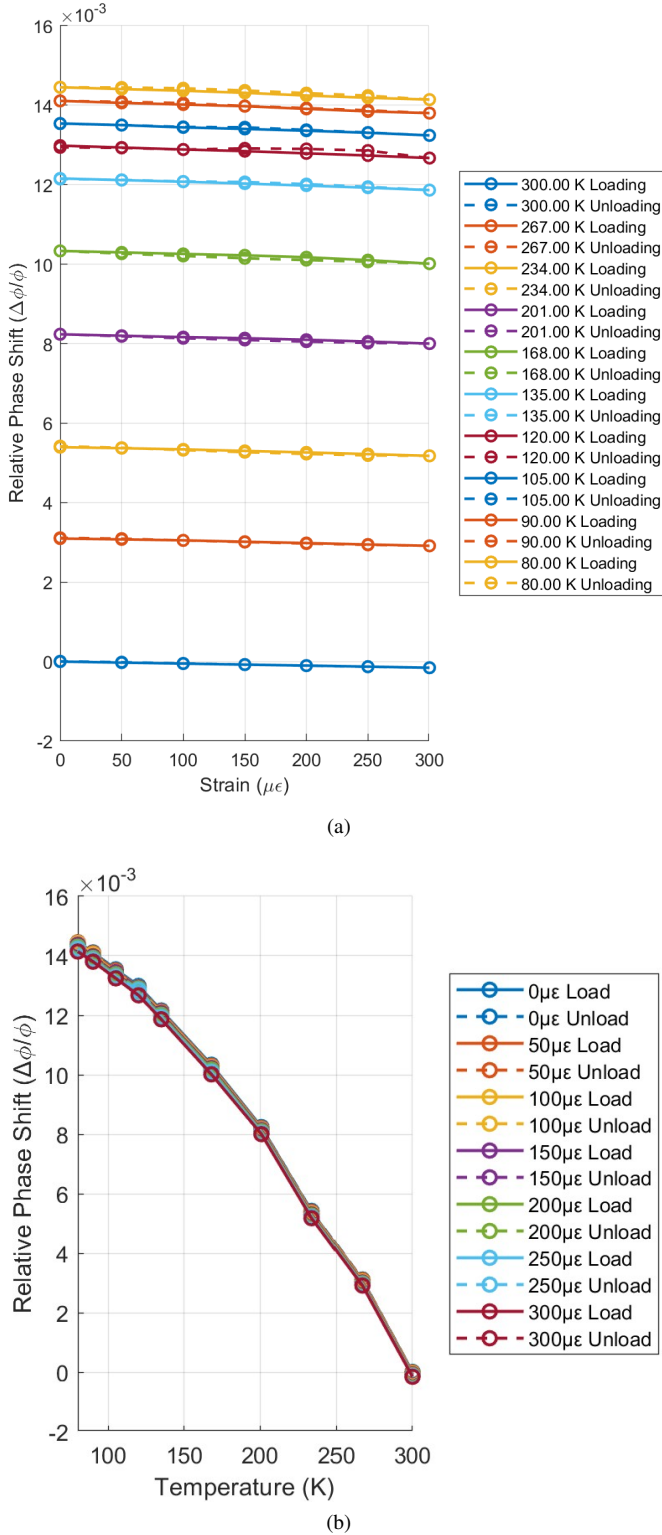


Fig. 5. (a) Relative phase shift versus applied strain (0–300 $\mu\epsilon$) at thermal set points from 300 K down to 80 K (trial 1 visual example). (b) Relative phase shift versus temperature for discrete strain levels from 0 to 300 $\mu\epsilon$. Solid lines denote loading and dashed lines denote unloading cycles across thermal set points from 300 K down to 80 K (trial 1 visual example).

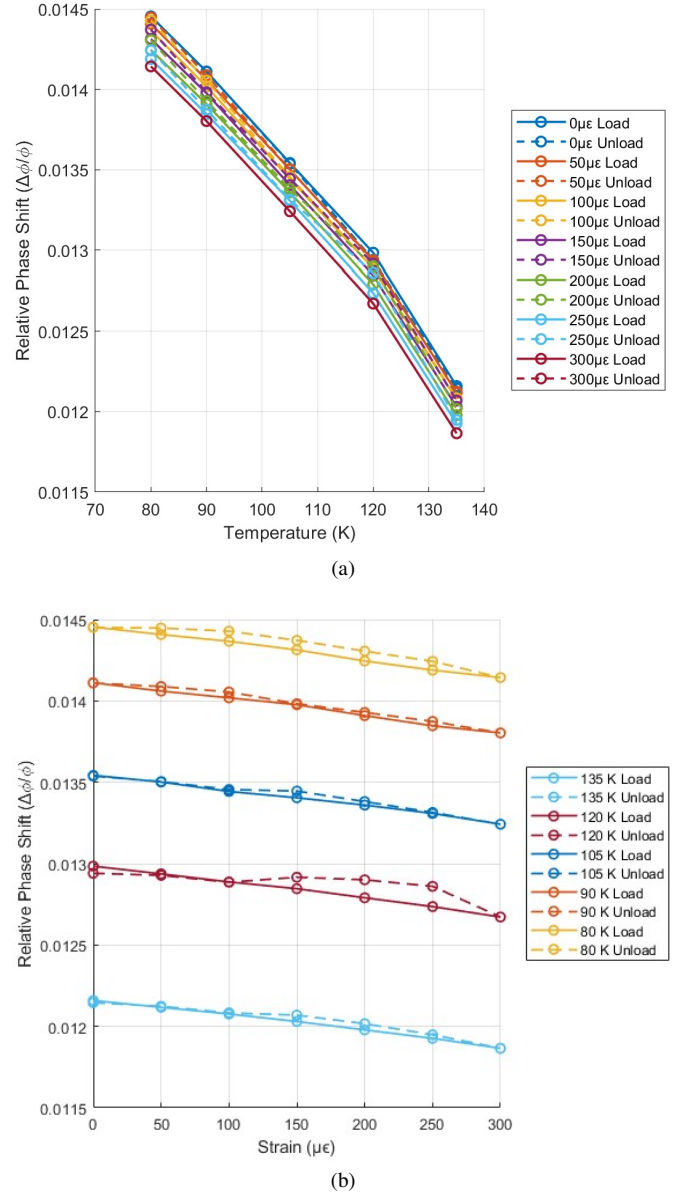


Fig. 6. (a) Relative phase shift versus cryogenic temperature (135–80 K) for discrete strain levels ranging from 0 to 300 $\mu\epsilon$ (trial 1 visual example). (b) Relative phase shift versus strain (0–300 $\mu\epsilon$) for selected cryogenic temperatures from 80 K to 135 K under both loading and unloading conditions (trial 1 visual example).

bonding process and exploring alternative fabrication methods could therefore help narrow the gap between simulation and experiment. For example, Nicolay *et al.* employed a reactive NanoFoil bonding technique, eliminating polymer layers and enhancing strain transfer under harsh conditions [39]. As future work, the impact of bonding material, thickness, application method, and wiring configuration on strain transfer and signal quality will be examined through multi-device testing under varied bonding conditions to better quantify adhesive and wiring induced error.

V. CONCLUSION

This work investigated the temperature and strain responses of SAW sensors based on 128°YX LN over temperatures

ranging from near room temperature down to cryogenic levels. In the lower-temperature regime (130 K–80 K), the experimentally determined TCD was approximately 47.66 ± 3.52 ppm/K, closely matching the FE simulation value of 46.24 ± 4.13 ppm/K. This close agreement verifies that the current models, incorporating higher-order elastic parameters, nonlinear thermal expansion, and Varshni-based elastic constants, accurately capture LN behavior under cryogenic conditions. Strain measurements indicate that the sensor exhibits an SCD ranging from about 0.53 ± 0.02 ppm/ $\mu\epsilon$ at 300 K to 1.05 ± 0.02 ppm/ $\mu\epsilon$ at 80 K. Although these values are lower than the analytical model value of 0.995 ppm/ $\mu\epsilon$ reported in literature at room temperature, the discrepancy is largely attributable to the adhesive layer's thickness and uniformity, which reduce strain transfer from the mounting structure. These bonding factors therefore remain a primary source of measurement error under cryogenic loading.

Overall, the findings address a critical gap in the cryogenic strain-sensing literature by demonstrating that SAW-based sensors retain consistent performance at low temperatures. Ongoing research will refine adhesive bonding and explore alternative solutions (e.g., NanoFoil) to improve strain transfer while continuing to enhance simulation fidelity below 80 K. To establish a clear performance benchmark under controlled conditions, we utilized a wired configuration, thereby eliminating uncertainties intrinsic to wireless interrogation (e.g., antenna coupling, radiation efficiency, environmental losses) and enabling direct assessment of the device's temperature-dependent response. Because low-temperature measurements of this kind have not previously been reported experimentally, starting with a wired approach was essential to isolate intrinsic device behavior. These measurements provide a baseline for direct comparison with future wireless implementations and will guide optimization of passive, wireless SAW sensors for multi-parameter sensing in extreme thermal and mechanical environments.

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